Author's response to anonymous review of " Sensitivity of iceberg drift and deterioration simulations to input data from different ocean, sea ice and atmosphere models in the Barents Sea (Part II)"

General Comments

This paper investigates the sensitivity of iceberg drift and deterioration simulations to varying input data from different ocean, sea ice, and atmospheric models in the Barents Sea. It provides a detailed numerical experiment using four combinations of environmental forcing data (Topaz, Barents-2.5, ERA5, and CARRA). The study emphasizes that iceberg drift and deterioration are particularly sensitive to the choice of ocean and sea ice forcing data (Topaz or Barents-2.5). While the combination of statistical analysis and individual case studies, such as the trajectory of iceberg 2013-788, adds depth to the study, I find some critical gaps and ambiguities in the paper.

[1] Thanks so much for your well laid-out summary. The authors' answers to your general and specific comments are given below. In addition, we provide suggestions on how the manuscript may be changed to satisfy your comments. We include a revised version of the conclusions to show an example of possible improvements to the manuscript with the help of the reviewer's comments. The rest of the manuscript will be revised at a later stage of the review process.

Revised conclusion:

In absence of sufficient iceberg observations in the Barents Sea, numerical simulations of iceberg drift and deterioration are the most reliable source of data for iceberg statistics. We forced a large number of iceberg trajectories with varying forcing conditions. We quantitatively confirm and novelly describe how the results of such simulations are sensitive to the input from ocean, sea ice and atmosphere reanalyses or forecasts. The findings may be used in the choice of forcing input and the critical analysis of iceberg model simulations.

We confirm that all forcing variables impact the iceberg simulations and quantify how the impact of atmospheric forcing is small compared to the impact of ocean and sea ice variables. Sea ice showed especially large influence on iceberg simulations, e.g. for the statistics of iceberg deterioration or the forcing along an exemplary iceberg trajectory. Sea ice decreases the iceberg deterioration, thereby increasing the length of the drift duration and trajectory. An extended drift duration and e.g. tidal looping increase the iceberg density, affecting the distribution in the domain. Thereby, difference in regional iceberg density and the spread of icebergs in the domain due to varied ocean and sea ice forcing can be high. The dependency of the simulation results on the environmental input data highlights the significant of the choice of such input data for the generation of iceberg statistics in the Barents Sea, e.g. for estimating the probability of iceberg exposure by structures and ships.

Although the forcing data has a strong influence on the results of iceberg simulations, it is possible that different combinations of input data yield similar overall results. Similarities in iceberg simulation results despite large forcing differences may be due to multiple compensating effects by varied forcing. Examples are found in a similar effective drift distance and southernmost extent despite large deviations in spatial SST, or similar seasonal cycle in iceberg extent despite deviations in onset of sea ice freeze-up and melt. Other similarities may derive from a similar representation of the year's conditions and regions in the forcing data sets, despite differences in other aspects of the data sets (e.g. multi-year variability of iceberg extent and similar characteristics for icebergs from the same source). We emphasise the general similarity in the main iceberg pathways, despite varied forcing. Those similarities may indicate *that the choice of forcing input has limited impact on some applications, e.g. estimating climatology of southernmost iceberg spread in the Barents Sea.*

We also showed how the assimilation of the forcing data into the iceberg model can be sensitive to the spatial and temporal resolution, bathymetry and coastline of the input data. In the setup of the iceberg model used in this study, the input data's characteristics steer from how far forcing data is assimilated and how representative it is. It influences the simulated iceberg distribution and extent in the domain and is especially visible along the coastlines. We highlight the importance of the forcing resolution's in coastal regions, despite the unreliable forcing information in those regions, due to the lack of other (environmental and iceberg) information. Although the conducted analysis is specific to the model setup, similar effects are expected to occur using other setups.

We highlight that the study is restricted to the years of 2010-2014 and 2020-2021, the Barents Sea, a selection of four environmental models and the specific setup of the iceberg model. This is due to temporal and spatial availability of the forcing data and the focus on the impact of varied forcing in the study. We also emphasise that we cannot provide clear suggestions on the best choice of forcing data in iceberg simulations, due to the diverse characteristics of the input data and the faceted impact on the simulations. However, the findings may be projectable on other settings and will facilitate the educated choice in forcing data.

Firstly, the motivation for this study is unclear. While the authors explicitly demonstrate differences in iceberg deterioration under various forcing scenarios, the key takeaway remains vague. What actionable insights can we derive from these results? Which combination provides the most reliable or "best" estimate of iceberg drift? Without addressing these questions, the practical value of this study seems limited.

[2] We attribute this confusion to the lack of sufficient clarifications in the manuscript which should certainly be improved. In the following, we argue that our study is novel and has a practical value, in more detail:

- The <u>motivation</u> of this study is that scientists and engineers in the field rely heavily on statistics of icebergs derived from numerical simulations of icebergs drift and deterioration. This is necessary due to the scarcity of iceberg observations, especially in the Barents Sea. As discovered earlier (Kubat et al. (2005, 2007); Eik (2009b, a); Keghouche et al. (2009, 2010)), the environmental forcing clearly steers the simulations results. Following, we need to estimate the impact of the environmental input on the simulation results. To the knowledge of the authors, no in-depth study of this nature is available, especially not with nowadays state-of-the-art environmental data. This suggests practical value and a high importance of the study for the field. Thereby, the selected environmental data reflects a small range of state-of-the-art environmental models that are likely chosen for simulating icebergs in the study domain.
- We understand the wish for clear outcomes and the rating of a "best estimate". The <u>key-takeaway</u> of this study is that we quantitatively confirm and describe the sensitivity of iceberg simulations to the selected environmental forcing. However, this study restrains from <u>rating best or most reliable estimates</u> for the following reasons:
  - We chose to restrain from varying the model settings to keep the focus on the effect of varying the environmental input data on the simulation results. Varying the model setting would have generated additional sample data that would easily clutter this study. Recall, the goal of this study is not to develop, verify and

validate a model, it is to study the effect of varying the environmental input data on the model results. Therefore, the choice of the model is trivial herein.

  - It is not easy to make a straightforward and simple suggestion about the suitability of the data for iceberg simulations, due to the fact that the environmental models perform better/worse in different regions and times. Although, this is inconvenient for the reader, different ocean, sea ice and atmospheric forcing variables may be differently suitable in different regions, during different time periods, for different variables, iceberg model settings and study goals.
    For example, Topaz and Barents-2.5 show clear advantages and disadvantages and are more/less accurate in different aspects. Topaz is coarser and neglects tides. Barents-2.5 aims at being more accurate with higher temporal and spatial resolution. However, it showed clear overestimation of sea ice. Other variables, such as ocean currents, are highly uncertain in both cases.
    Iceberg models treat the forcing data differently and are differently tuned, which may cause better results with one or the other forcing.
  - The suitability of the forcing also depends on the simulation goal (e.g. statistics of iceberg occurrence or individual trajectories) and which processes it should represent (e.g. tides).
  - Instead of judging the suitability of the forcing input, we tried to outline which specific characteristics of an individual model (e.g. tides in Barents-2.5) cause which impact in iceberg simulations (e.g. spatial distribution). Other planned studies will concern themselves with rating the performance of the iceberg simulations under varied forcing by comparing to iceberg drift observations.
- Based on the reviewer's comments, we suggest following changes in the manuscript.
  - We will highlight the motivation and importance of the study even more.
  - Further, we will outline the settings, scope and limitations more clearly.

Secondly, the temporal scope of the analysis raises concerns. The authors focus on limited time windows (2010–2014, 2020–2021), and yet they find that atmospheric forcing has only minor effects. Why not extend the analysis to the longer overlapping period (2010–2022) available for Topaz, Barents-2.5, and ERA5? This would allow for a more robust assessment of iceberg occurrences and their trends over the full 12 years. The decision to restrict the study to only seven years until the end is not adequately justified.

[3]

- The choice of limiting the analysis on the years 2010-2014 and 2020-2022 was entirely based on the limited availability of the Barents-2.5 hindcast product, at the time the study was conducted. (CARRA was available for the full time period all the time.) We wanted to include the largest number of years possible, causing the un-intuitive break between 2014 and 2020. Although large variability exists from year to year, we also believe that these two periods might at least characterise the different decades with different sea ice regimes to some point.
  - We suggest to describe the reasoning behind the temporal limitations more clearly in the manuscript.
    - "The simulations are performed for the years 2010-2014 and 2020-2021 (7 years), which are the only years all forcing datasets were available at the time the simulations were performed. Future studies may concern themselves with analysing the newly available, extended time period."

Thirdly, the use of the nearest-neighbor scheme for environmental forcing is perplexing. The authors spend considerable text explaining the process, but why was this method chosen over more commonly used interpolation techniques such as linear or inverse distance weighting? How can the errors introduced by this nearest-neighbor approach, especially near coastlines, be quantified? This choice introduces uncertainty, which is not thoroughly analyzed.
[4]

- Thank you for highlighting the downside of this set-up. We fully agree on the availability of more accurate weighting and interpolation approaches. However, as mentioned above, this study does not aim to analyse or improve the iceberg model setup. Instead, the iceberg model was inherited from Monteban (2020) with most of the settings and kept constant during the experiment. Amongst others, this includes assimilating of the environmental forcing from the nearest grid cell and 2-hourly time steps. As this study does not concern itself with optimising the model setup, quantifying the error induced by nearest neighbour approach is also not part of this study.
- The data assimilation method was described thoroughly in the manuscript on-hand, as in-accurate implementation can lead to physically wrong results. The authors therefore tried to assure the reproducibility of the study.
    - We therefore suggest to mention the existence of more accurate assimilation methods. We also suggest to take away the focus from the data assimilation method, to not confuse the reader about the goals and scope of the work.
    - The description of the assimilation method explains the data pre-processing methods in part I and is the base for the analysis of forcing data availability (Section 4.1). Section 4.1 provided very interesting results, that we wanted to include. It may be transferable on more accurate assimilation techniques, as they all have the problem of missing data e.g. along the coastlines.
    - We know see that Section 4.1 is very specific to the used iceberg model setup and that it may not be easy to transfer the knowledge on other assimilation techniques. If the reviewer or editor think that it would enhance the readability of the paper, we would be able to exclude Section 4.1 and the detailed description of the data assimilation/resampling methods from the manuscript of Part I and II.

Finally, Table 1 lacks clarity regarding the spatial resolution used in each test.
[5]

- All environmental data has been used at original spatial resolution. The iceberg model itself is grid-less.
- We suggest to add the spatial resolution (and variables, see answer [10]) of the environmental datasets to Table 1:

Objective	*Ocean & sea ice Forcing *, spatial, temp. resolution*	*Atmospheric Forcing **, spatial, temp. resolution*
Reference	*Topaz, 12.4 km, daily*	*ERA5, 31 km, hourly*
Regional wind	*Topaz, 12.4 km, daily*	*CARRA, 2.5 km, 3-hourly*
Regional ocean & sea ice	*Barents-2.5, 2.5 km, hourly*	*ERA5, 31 km, hourly*
High resolution, fully regional	*Barents-2.5, 2.5 km, hourly*	*CARRA, 2.5 k, 3-hourly*

** Ocean & sea ice variables: sea surface velocity (vw), surface temperature (SST), sea ice concentration (CI), thickness (hsi) and drift velocity (vsi)*
*** Atmospheric variables: 10m wind (va)*

In a sensitivity analysis, it is critical to change one parameter (e.g., spatial resolution, ocean/ice forcing, or atmospheric forcing) while keeping the others constant.
[6]

- We agree that this is the set up of a full sensibility analysis. In this study, we did not perform full sensitivity analysis, as changing out individual variables or changing resolutions is not a typical use case (see Section). In typical use case, a number of variables will be adapted from one environmental dataset and a number of variables will be taken from other datasets at their respective original resolution and with the respective physical description. We tried to follow the most-likely use case with common environmental models for atmosphere, and ocean/sea ice separately, at their original resolution and interpretation of the variables. The aim of this approach is to show the impact of the forcing data, that may occur in any iceberg simulation as realistic as possible.
- Another reason for this approach was consistency within the forcing input. Changing individual variables and their resolution may give inconsistent forcing (e.g. between sea surface temperature and sea ice concentration).
- We suggest to describe this approach more clearly in the manuscript to avoid confusions with a full sensitivity analysis.
  - Line 59-60: "*We did not conduct a full sensitivity, analysis exchanging every variable individually, to avoid physically inconsistent forcing (of e.g. SST and CI) and to resemble a probable use case as closely as possible.*"
  - *Add at line 72: "All environmental data is used at original spatial resolution, which is indicated in Table 1".*

The reference setting for the experiments remains unclear.
[7] We are unsure if this question relates to the setting of the reference experiment (Topaz,ERA5) or the fixed settings of the iceberg model.

- The settings of the iceberg model are largely adapted from Monteban (2020), that did the latest contribution to the underlaying iceberg model. Those are described in Section 2.4 and the Appendix.
- The setting of the reference experiment is recreated from Monteban (2020), using ocean and sea ice variables from the Arctic Oceans Physics Reanalsyis (Topaz4) and wind from ERA5. Due to the common use of those models and their good spatial and temporal availability, we consider this a valid choice. The choice in iceberg seeding is based on observed size distributions and numbers of iceberg, as presented by Monteban (2020).
- We can try to describe those settings more clearly, if wanted.

And why keeps the original resolution instead of interpolating into different resolution?
[8] The authors don't see reasons to change the resolution of the input data in this study. The reasoning for the approach of using original resolution is described in answer [6].

In summary, the paper has potential but requires major revisions to address these concerns before it can be considered for publication.
<u>Specific Comments:</u>
1. Figures: Please review all figures to ensure the color legends are consistent and correctly labeled.
[9] Thank you for pointing this out. We will assure this in the next review stage.

2. Line 59: I am not sure that I totally get the sentence, since you must list the rationale for selecting datasets (e.g., Topaz and CARRA) for specific variables like regional wind

and their respective resolutions needs to be explicitly stated.
[10] Thank for pointing this out. We will try to describe this more clearly. We suggest to add the variables and resolution to Table 1 (see in answer [5]). Further We suggest to change the text of Section 2.1, e.g.

- Line 57: *The forcing combinations represent a reference case with global forcing (Topaz,12.4 km and ERA5, 31 km) and a high-resolution, regional simulation (with Barents-2.5 and CARRA, both 2.5 km).*
- Line 58-59: *The combinations Topaz and CARRA (12.4 km, 2.5 km) and Barents-2.5 and ERA5 (2.5 km, 31 km) serve to estimate the individual influence of ocean, sea ice and atmosphere forcing on the simulations results.*

The reasoning for not conducting a full sensitivity analysis is explained in answer [6] and the line 59-60 will be improved as described.

3. Line 99: Why were 2-hourly time steps chosen? Could hourly time steps provide a more precise representation of iceberg drift? Please clarify if 2-hourly intervals are sufficient.
[11] The 2-hourly time steps derive from the model setup, inherited from Monteban (2020). In this set-up, ocean and sea ice variables are provided at daily frequency (Topaz) and ERA5 data is available hourly, read 2-hourly, but does not influence the simulations to a large degree. Thus 2-hourly time steps are feasible for the reference case. CARRA is only available 3-hourly. The Barents-2.5 data now offers the opportunity of hourly ocean and sea ice forcing. Thus, hourly simulation time steps (and assimilation of the forcing data) may have increased accuracy of the representation of the fast processes. However, as described in answer [2], the goal of the study is not to analyse the impact of the model settings.

- We suggest to describe the scope and limitations of the study more explicitly, as mentioned in answers [2,4].

4. Line 105-106: The reasoning for using the nearest-neighbor scheme is unclear. This method is known to be less accurate, especially near coastlines. Why was it chosen over more sophisticated interpolation methods? How do you quantify the associated errors?
[12] See answer [4].

5. Figure 7, The influence of bathymetry on Topaz+ERA5 and Topaz+CARRA combinations is intriguing. Could you elaborate on whether this arises from assimilation processes or the original resolution of the models? How can you ensure the observed differences are due to the coarse resolution of ERA5? Are these differences consistently observed in other trajectories over the same regions?
[13]

- The observed differences of the trajectories 2013-788 forced by Topaz+ERA5 and Topaz+CARRA are likely a <u>combinations of effects</u> from horizontal resolution (and topography near coast), assimilation technique, representation of wind over sea ice and growing difference after small initial perturbation.
- The <u>bathymetry/topography</u> should not cause any difference in between the simulated trajectories of Topaz+ERA5 and Topaz+CARRA in distance (>31 km) to the coast. A very small amount of simulated time steps is close to the coastline (e.g. around Kong Karls Land), where the large differences in the wind data exist.
- The <u>assimilation technique</u> is similar for ERA5 and CARRA. As a direct effect of spatial resolution, coarser ERA5 resolution cause larger maximum search radii, potentially making the assimilated data less representative for the iceberg position.
- ERA5 and CARRA are very similar over open ocean (e.g. Køltzow, 2022). Part 1 of this study revealed a systematic difference of ERA5 and CARRA <u>over sea ice</u>, which may

cause the differences in the trajectories in Figure 7, as sea ice is shown by Topaz from late November 2013 to late April 2014.

- We should also keep in mind, that small initial difference in (wind-) forcing may cause small differences in iceberg position, which can turn into large difference of the trajectory in the end.
- Thus, the differently resolved wind input causes difference in the simulated trajectory 2013-788
    - ..due to differently resolved topography along the coastlines.
    - ..due to larger search radius during the assimilation process.

  But differences are also caused by different physical representation of the variable (e.g. over sea ice) and growing difference,
- Visible differences of the simulations forced by Topaz+ERA5 and Topaz+CARRA are also found <u>in the statistics</u> of spatial density (Figure 5). Figure 5 shows how often, how long and how many icebergs reside in different regions of the Barents Sea. Figure 5c varies the atmospheric forcing under Topaz forcing and shows how ERA5 and CARRA cause different density, also along the trajectory of iceberg 2013-788. The same is observed for varied atmospheric under Barents-2.5. Thus, the results of the statistical analysis support the mentioned differences observed for iceberg 2013-788.
- I suggest to add to the (or describe more clearly in the) discussion of the trajectory:
    - Difference between trajectory is likely a combination of effects, also describing the effects.
    - Connect differences in trajectory 2013-788 with results from density maps.

6. Line 433: I am not sure I can get the logics in the discussion on compensatory effects (e.g., similarities in iceberg pathways despite large differences in forcing). Did you compare products with the same forcing but at different resolutions? A clearer explanation is needed.

[14] Thank you for pointing out the lack of clarity concerning the compensatory effects.

- We only worked with the original resolution of the products, however the input comes at different (original) resolutions.
- The mentioned compensatory effects (e.g., similarities in iceberg pathways despite large differences in forcing) derive from the interplay of effects, such as those from provided resolution, but also physical representation of the variables.
- Note, why this study does not contain a full sensitivity analysis, in answer [6].
- We suggest that to review the discussion concerning the mentioned points.

7. I am not sure if I am convined by just one case in Sec 3.6, did you find some common features based on all extreme case? Relying on a single case study is insufficient to draw broader conclusions. It would be better to incorporate additional deterioration processes into the model to better capture iceberg dynamics under extreme conditions.

[15]

- We agree that <u>broad conclusions</u> cannot be drawn from one example. The example of the trajectory 2013-788 is meant to illustrate the conclusions from the statistical analysis, rather than to draw new conclusions. One example for this is described in answer [13].
- We analysed the trajectories that reached the furthest south and did not find obvious common features. However, it is not a key-part of this study to analyse extreme cases. This study focusses on the average states (e.g. average difference that is induced by the forcing). The statistics of iceberg forcing, drift, melt and occurrence are created by seeding icebergs at random dates and (to an extend) positions, introducing a random

selection of environmental conditions. Those statistics likely include extreme forcing conditions and extreme iceberg extend, but aim at representing the mean state.

- Iceberg 2013-788 is a case of exceptional southward drift, but not due to extreme forcing. It is discussed in the manuscript, why the trajectory is shown, despite its incapability of representing an average state.
- No additional deterioration processes are added to the iceberg model, as this study restrains from analysing the effect of the models settings in the simulation results (see answer [4]).
- We suggest to review the discussion (of the example trajectory) to make it more clear to the reader, that we do not draw conclusions from the example trajectory, but that it only illustrates found conclusions. we also suggest once again to highlight the scope and limitations of the study more clearly.

8. Mechnism analysis: I would also love to see more mechanism anslysis about wave erosion, basal melt, and buoyant convection since it exactly shows how iceberg react to different forcings. This would clarify how icebergs respond to different forcing conditions. Additionally, could you explore ways to incorporate the uncertainties related to solar radiation, calving, and wave interactions, which are currently simplified in the model?

[16]

- We initially studied the <u>reaction of the icebergs to different forcing</u> concerning melt processes in more detail. However, we decided to not present it in the manuscript, as the results were not very clear, did not contribute to the conclusions and the page limit was reached. A shortened version of the findings is still presented in Section 3.2.
- <u>Wave erosion and calving</u> are complex mechanisms that deserve dedicated studies. The interaction of iceberg and waves is under current study by other researchers, and is outside the scope of this manuscript. Other iceberg models assimilate wave data and simulate wave erosion in a more complex manner, making those models more suitable for the task. For more, this study does not analyse the iceberg model settings (answer [4]).
- <u>Solar radiation</u> is neglected in this case, due to the high latitudes. I suggest to make following changes:
  - Line 588: "In this study, the effect of solar radiation and forced convection by wind is neglected, due to their comparably small contribution (Savage, 2001), especially for small icebergs and high latitudes."
- A <u>uncertainty analysis</u> would be a very meaningful contribution. However, a uncertainty analysis concerning the melt terms of the iceberg model (and thus the model settings) is not goal of this study (see answer [4]). An analysis of the uncertainty induced by the uncertain input data is hopefully subject of future studies. This study is about the impact of forcing differences (by the model setup, resolution and also uncertainties), thus, may lead the way to this natural next step. However, I want to remind about the scope and page-limit of this study.
- We hope this comment can be resolved by outlining the scope of the study and inform about the reasoning for the model settings and analysis choices better in the reviewed manuscript.

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